CPC2 on the Hipparcos System

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ABSTRACT

The Second Cape Photographic Catalog (CPC2) is an astrometric, photographic catalog covering the entire Southern Hemisphere to a limiting magnitude of about 10.5. The Hipparcos Catalogue has been used for a new plate–by–plate rigorous reduction. A significant improvement over the release 1 version of the data was achieved. With an average accuracy of 53 milliarcsecond (mas) and a mean epoch of 1968, the CPC2 is a key catalog for proper motion determination. This release 2 of the CPC2 contains high quality positions of 266629 stars and an appendix of 8040 other stars. Catalog reduction and construction details are given as well as a description of the final product, which is available from the U.S.Naval Observatory.

Subject headings: astrometry, position catalog, Southern Hemisphere

1. Introduction

The Second Cape Photographic Catalog (CPC2) is an astrometric survey based on 5687 plates taken at the Cape Observatory during the time period of 1962 to 1973, with a mean epoch of 1968. Positions for a total of 274669 stars in the V magnitude range of about 6 to 10.5 are given in this catalog. The first release of the CPC2 (de Vegt et al. 1993, Zacharias et al. 1992) was based on the Southern Reference Star (SRS) Catalog (Smith et al. 1990). This second release is based on the Hipparcos Catalogue (ESA 1997), with greatly improved precision, accuracy and density of reference stars to reduce the plate data. First results from this rigorous new reduction have been presented already (Zacharias et al. 1997a), and a summary of these reductions with implications for proper motion determination was given elsewhere (Zacharias et al. 1999). This paper describes the final product, which is available from the U.S. Naval Observatory (see http://www.usno.navy.mil/ad.html).

A further refinement in the plate reductions, a block adjustment (Eichhorn 1960) of the data, is planned. The block adjustment of the CPC2 data is expected to improve the catalog only slightly (Zacharias 1992) over the current version. The major improvement is the step from using transit circle reference star data to Hipparcos, even in a conventional plate adjustment. In order to serve the astronomical community, it was decided to release this CPC2 version now.

With its high accuracy and weighted mean epoch almost midway between the Astrographic Catalogue (AC) (Urban et al. 1997) and the Tycho Catalogue (ESA 1997), the CPC2 is an important catalog for proper motion determination of stars in the 9 to 11 magnitude range in the Southern Hemisphere. In the past, the CPC2 was a major contributor for the Hipparcos Input Catalogue (INCA) (Turon et al. 1992), as well as for the compiled astrometric catalogs ACRS (Corbin & Urban 1992) and PPM (Röser & Bastian 1993).

2. Observations

For details about the project history the reader is referred to the papers mentioned in the introduction. A short summary is given here. The project was started in the early 1960's using a new 4–component lens of 200 mm aperture, a plate scale of 100"/mm and a field size of 4.07 degrees. The plates were taken in declination zones, starting with the −40° to −52° zone (the original AC Cape Zone), taken in 1962–63. In 1966 the observations continued with the −30° to −40° zone, followed by the remaining zones of the Southern Hemisphere. Observations were completed in 1973. The plates were taken in a 4–fold overlap pattern. Two exposures of usually 3 minutes duration were taken on each plate, thus there is normally a total of 8 images for each star and even more for stars close to the pole where plates overlap more than average. The astrometric limiting magnitude is about 10.5. Contrary to earlier photographic surveys, a visual–red spectral bandpass (530–640 nm) was used with the benefit of reduced refraction effects due to the Earth's atmosphere. The magnitudes given in the first and this CPC2 release are photographic magnitudes in that spectral bandpass, thus between V and R, with an estimated error of 0.1 to 0.3 mag. Magnitudes of about 4.0 or brighter are doubtful. Stars of magnitude 6.0 or brighter are affected by the proximity of the images of the 2 exposures per plate. All plates were measured on the GALAXY machine at the Royal Greenwich Observatory (RGO) concluding in 1984. The measurements were transferred to Hamburg Observatory for astrometric reductions (release 1). The data later went to the U.S.Naval Observatory, where the present catalog was constructed.

3. Reductions

3.1. Reference Stars and x, y–data

Only the 50629 Hipparcos stars flagged as "good" astrometric (blank field H10 = reference flag for astromety in the Hipparcos Catalogue) within the area covered by the CPC2 plates have been used. Of these, 50569 could be uniquely matched with the x, y data and were used as reference stars. The mean standard error of a Hipparcos star position at the mean epoch of the CPC2 data is about 30 mas per coordinate. Due to the large plate size (4.07°) an average of 40 Hipparcos stars could be utilized per plate, while 13 and 88 where the smallest and largest numbers respectively.

The mean precision of the x, y measurements is 113 mas (1.13 μm) per image and coordinate (global internal error, see also Zacharias et al. 1992). As with the release 1 data, also here the 2 exposures per plate have been combined using a linear transformation model, prior to any further reductions. In the following we refer to this as "single" image (position), meaning coming from a single plate as opposed to a mean position derived from several plates. Thus the precision of these single images is about $113/\sqrt{(2)} = 80$ mas per coordinate, neglecting correlations between the images.

3.2. Basic Conventional Plate Adjustment

Initially an 8–parameter plate model was used, which includes linear and plate tilt terms for the mapping model of the tangential coordinates to the xy–data. Weights were used in the least–squares adjustment derived from the individual formal position errors of the Hipparcos stars at the epoch of the plate plus the assumed uncertainty in the x, y measures (80 mas per coordinate). A 3σ criterion was used to reject outliers. If the sigma of the adjustment exceeded 1.5 times the expected value, the largest residual was removed

and the reduction repeated. Rigorous apparent place and refraction routines were used for the reference stars prior to a projection onto the tangential plane. After adjustment, all photographic positions were back–transformed into mean places.

3.3. Initial Distortion Correction

First, systematic errors as a function of the x, y–coordinates have been investigated, using the residuals of the preliminary reduction with the basic model (see above). In a pilot investigation the third order optical distortion term was determined to be approximately 40 mas/degree^3. Corrections for this term were applied to the x, y–data prior to the following reductions. Next, using an 8–parameter model (linear and tilt terms), all residuals were binned as a function of the x and y coordinates, resulting in a field distortion pattern (FDP), which was published elsewhere (Zacharias et al. 1997a). This new FDP looks almost identical to the one derived from CPC2 release 1 data, based on SRS reference stars (Zacharias 1995). The quadratic mean correction due to the field distortions is 0.4 and 0.35 μm for the x and y coordinate, respectively. Thus these corrections are orders of magnitude smaller than for typical Schmidt plates. The final FDP was generated by slightly smoothing and interpolating the original FDP, a grid of 17 by 17 residual vectors. Using a look–up table by coordinates, the FDP was applied to the raw x, y–data prior to the following reduction steps.

3.4. Magnitude Dependent Systematic Errors

Next, systematic errors as a function of magnitude were investigated. Magnitude equations in the CPC2 data strongly depend on the declination zone. With the use of Hipparcos reference stars the systematic errors in the x, y–data are more clearly seen,

however, the overall pattern is the same as was already found in the CPC2 release 1 data. For detailed plots see (Zacharias et al. 1992, Zacharias et al. 1997a). Tests were also made using a plate model including linear magnitude terms, thus allowing these systematic errors to be solved on a plate–by–plate basis. However, even with the large number of reference stars available, the formal errors on the determined parameters degraded unacceptably without clear benefit, so a zonal correction method was adopted instead. For all zones, a linear correction of the coordinates as a function of magnitude was found to be sufficient. Slope coefficients, s_x, s_y, were obtained from linear fits through the residuals vs. magnitude plots for each declination zone. New, corrected x_{cor}, y_{cor} coordinates were obtained from uncorrected x, y–data by applying the following,

$$x_{cor} = x + s_x(m - m_0)$$

$$y_{cor} = y + s_y(m - m_0)$$

with all x, y coordinates measured in mas, m is the CPC2 photographic magnitude (between V and R) of a given star and m_0 is the mean photographic magnitude of a given sample (usually around 8.3^m). Residuals from a conventional plate adjustment with the magnitude equation corrected, still showed some systematics. Empirically the previously obtained slope parameters were scaled by factors (about 1.5) and the process iterated until the systematic error was fully corrected. The final coefficients for all corrections of the x, y–data as a function of magnitude are given in Table 1.

After solving for the pure magnitude equation, residuals were plotted vs. the product of Δmag and the coordinates (as measured from the center of the plate). Systematic errors were detected, which are called coma terms. An example plot is given elsewhere (Zacharias et al. 1997a). Corrections were applied to the x, y–data according to

$$x_{cor} = x + c_x(m - m_0)x\prime$$

$$y_{cor} = y + c_y(m - m_0)y'$$

The coefficients for coma corrections, c_x, c_y are also given in Table 1. Again, x_{cor}, y_{cor} and x, y are in mas, however x', y' are in degrees. Coma terms are significant in this investigation using the Hipparcos stars, they were not in the CPC2 release 1 reductions due to inferior reference star data. Applying the corrections for magnitude and coma terms did not improve the individual plate reduction sigma by much (few percent), however systematic errors up to about 100 mas could be removed this way.

3.5. Final Distortion Correction

After corrections for magnitude dependent systematic errors were completed, the FDP was investigated again. Now slight differences were found as a function of the declination zone. The data were split into 3 areas, the Cape Zone, with plate centers in the range of $-40°$ to $-52°$, the $-29°$ to $-39°$ zone and the remaining zones. For each area an individual FDP was generated and applied in the same way as described above. After 2 iterations the remaining FDP essentially vanished.

3.6. Color Terms

Finally, systematic errors depending on the colors of the stars have been investigated, using the (B-V) color index from the Hipparcos Catalogue. Only for parts of the third area (outside the $-29°$ to $-52°$ zones) these errors were found to be significant and corrections were applied according to

$$y_{cor} = y + l_y((B - V) - (B - V)_0)$$

for the 0° to −28° zones, where $(B-V)_0$ is the mean color index for a given sample. Corrections needed to be applied only for the y–coordinate, the l_y parameters are also given in Table 1. In addition a small offset of 20 mas (instead of a linear function) was applied to the y–coordinate for the −69° to −90° zone for $-1.0 \leq (B-V) \leq 0.2$. In order to be able to apply these corrections also to the field star positions, the Tycho (B-V)'s were used. Virtually all CPC2 stars are included in the Tycho Catalogue (ESA 1997).

3.7. Final Plate Solution

The x, y–data were corrected for an average 3rd order optical distortion term, field distortion pattern, magnitude, coma and color terms, as described above. Rigorous refraction and apparent place routines were applied. A 9–parameter plate model, with 6 linear (a to f), 2 tilt (p, q) and 1 distortion parameter (D) was used in a weighted least–squares adjustment for each plate individually.

$$\begin{aligned} \xi = \; & ax \; + by \; + c \; + \epsilon x \; + fy \; + px^2 \; + qxy \; + Dxr^2 \\ \eta = \; & -bx \; + ay \; + d \; + fx \; - \epsilon y \; + pxy \; + qy^2 \; + Dyr^2 \end{aligned}$$

Here ξ, η are standard coordinates and x, y the measured coordinates, while r^2 stands for $x^2 + y^2$. The distortion parameter (D) gives corrections to the average 3rd order optical distortion on a plate–by–plate basis. Including this parameter was found necessary because of a significant variation from plate to plate. The large number of available reference stars per plate made this approach feasible. The mean adjustment error was found to be 88 mas, which is the quadratic sum of the mean reference star precision at epoch of the plates and the mean x, y measuring precision. Figures 1 to 3 show the residuals in x and y plotted vs. magnitude, coma and color, respectively for the entire catalog data. A total of 209000 residuals per coordinate were used, excluding individual residuals larger than

500 mas. Instead of x, y–components, the residual vectors can also be split up into radial and tangential components. Fig. 4 shows the radial residuals vs. radius. The data are well corrected out to the edge of the plates. The tangential residual distribution looks very similar. All those systematic errors are corrected to within about 10 mas. Taking quadratic means of individual residuals gives a measure for σ_x and σ_y, which are plotted vs. plate epoch in Fig. 5. The early epoch data have a slightly larger random error than the later epoch data, likely to be caused by the larger epoch difference of that zone to the central Hipparcos epoch (1991.25).

3.8. Mean Positions

The individual photographic positions from the plate–by–plate solution as described above have been combined to mean catalog positions as follows. Weights for each individual image coordinate were calculated based on the assumed mean measuring precision and the error propagation contribution due to the plate parameter uncertainties (Eichhorn & Williams 1963). The correlation of star positions from overlapping plates due to a subset of common reference stars has been neglected here. Then a weighted mean position and mean epoch was calculated, with outliers excluded. For stars with only one individual position, the error calculated in the weighting procedure was used, thus it is always only slightly larger than 80 mas, the assumed x, y–measuring precision.

4. The Catalog

The final catalog of the CPC2 release 2 is presented in 2 parts. Both parts are sorted by declination. The main catalog contains 266629 stars with at least 2 images per star and a formal position error of 53 mas on average, with a cutoff of 200 mas per coordinate on

individual stars. As an appendix, the second part contains an additional 8040 stars. Those are the stars with a formal error exceeding the 200 mas in one or the other coordinate, as well as all the single–image stars. The formal errors on the single–image stars might be grossly wrong. A total of 1462 stars, which were included in the release 1 catalog have been entirely dropped in this release, due to unresolved problems, showing a formal error of 500 mas or larger in at least one coordinate. Matching of individual images has been taken over from the original work made at RGO and no problem case study was made with this investigation. Also, the photometry given in the release 2 was retained from the release 1, however magnitudes are now rounded to 1/10 to better indicate the precision of these photographic magnitudes. Magnitudes less than about 4.0 are doubtful. CPC2 positions and magnitudes of stars brighter than about 6th magnitude in general have to be taken with caution due to overexposure effects on the plates.

The precision of the CPC2 catalog is a function of magnitude, which is illustrated in Fig. 6, showing the results for the main part of this release. Figure 7 shows the distribution of the catalog precision. Table 2 gives an example of the catalog data, both parts being in the same format. Table 3 explains this format. All entries are integer, all columns are separated by at least one blank. Note, instead of the declination, the always positive south polar distance (SPD) is given, which equals the declination plus 90 degree.

5. Conclusions

The CPC2 data have been brought successfully onto the Hipparcos system by a complete new reduction based on first principles. Remaining systematic errors are believed to be on the 10 mas level or below. The high accuracy and density of the Hipparcos Catalogue as compared to the previously used reference star catalog allowed for a much more detailed study of systematic errors in the x, y–data. The propagation of errors from

the adjustment parameters to the field star positions is also significantly reduced in this release 2 as compared to release 1, resulting in smaller random errors. However, major systematic errors, such as the FDP and magnitude terms, were found to be essentially unchanged between the two releases.

The released data comprise an observational position catalog without proper motions. Due to its high accuracy and intermediate epoch, the CPC2 is essential for proper motion determinations in the Southern Hemisphere when combined with other data such as the AC (Urban et al. 1997) and the UCAC–S (Gauss et al. 1996, Zacharias et al. 1997b). Due to its 4–fold overlap the CPC2 data are most suitable for a rigorous block adjustment, which will further improve the precision and accuracy of the catalog, however only slightly over the version presented here.

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REFERENCES

Corbin,T.E. & Urban,S.E. 1992, Astrographic Catalogue Reference Stars (ACRS), U.S.Naval Observatory, Washington D.C.

de Vegt, C., Murray, C.A., Zacharias, N., Nicholson, W., Penston, M.J., Clube, S.V.M., 1993, A&A Supl, 97, 985

Eichhorn, H., 1960, AN 285, 253

Eichhorn, H. & Williams, C.A., 1963, AJ 68, 221

ESA, 1997, The Hipparcos and Tycho Catalogues, ESA SP–1200

Gauss, F.S., Zacharias, N., Rafferty, T.J., Germain, M.E., Holdenried, E.R., Pohlman, J.W., Zacharias, M.I., 1996, BAAS 28, No.4, 1282

Röser,S. & Bastian,U., 1993, PPM Vol.III,IV, The PPM–South Catalogue, Spektrum Akademischer Verlag, Heidelberg

Smith, C.A., Corbin, T.E., Hughes, J.A., et al., 1990, in Proceedings of the IAU Sympos. 141, p.457, Leningrad

Turon,C. et al., 1992, The Hipparcos Input Catalogue, ESA SP–1136

Urban,S.E., Corbin,T.E., Wycoff,G.L., Martin, J.C., Jackson, E.S., Zacharias, M.I., & Hall, D.M., 1997, AC2000, AJ 115, 1223

Zacharias, N., 1992, A&A, 264, 296

Zacharias, N., de Vegt, C., Nicholson, W., Penston, M. J., 1992, A&A, 254, 397

Zacharias, N., 1995, AJ 109, 1880

Zacharias, N., de Vegt, C., Murray, C.A., 1997a, in Proceedings of Hipparcos–Venice 97, p.85, ESA SP–402

Zacharias, N., Germain, M.E., Rafferty, T.J., 1997b, in Proceedings of Hipparcos–Venice 97, p.177, ESA SP–402

Zacharias, N., Zacharias, M.I., de Vegt, C., & Murray,C.A., 1999, in Highlights of Astronomy, IAU GA Kyoto (in press)

Table 1: Magnitude equation, coma and color terms.

DEC		(mas/mag)			(mas/mag deg)	
center		s_x	s_y	l_y	c_x	c_y
0	−8	+2.7	−59.6	−10.6	+12.1	+5.4
−10	−18	+4.2	−51.0	−92.3	+11.6	+6.5
−20	−28	+5.4	−41.6	−64.7	+10.7	+6.0
−30	−38	−2.9	+23.1	0.0	+5.8	+0.6
−40	−52	+21.8	+23.0	0.0	+15.5	+18.5
−54	−68	+5.5	−5.0	0.0	+10.8	+5.4
−70	−90	+3.4	+5.8	0.0	+9.0	+3.7

Table 2: Example of the catalog format showing the first and last 10 lines of the main catalog and appendix.

CPC2	mag	RA	SPD	sx	sy	nu	epRA	epDC
10023	87	484827421	607449	17	36	10	70808	70827
10026	104	18267827	681919	19	62	7	70900	70885
10024	81	537107841	782928	17	28	10	70809	70832
10028	66	787998323	822048	28	16	9	71065	71030
10016	105	325910460	1168541	113	5	2	70655	70614
10045	102	1244856579	1219043	63	63	11	71273	71208
10015	103	352851687	1533862	192	109	3	71462	71454
10019	103	436269404	1600738	52	55	7	71000	70950
10027	103	726149169	1620601	43	177	3	71404	71407
10011	97	318075719	1899667	30	32	10	70866	70846
920025	95	24575777	331773166	56	193	2	70165	69764
920037	91	29436160	331777744	37	87	2	69476	69584
923304	97	1247312709	331798301	77	122	2	69892	70047
923086	94	1182749563	331801002	31	86	2	68699	68699
920201	100	100775026	331865304	48	126	2	68945	68945
923114	100	1191141695	331876677	104	19	2	70570	70570
920175	88	89442269	331886622	31	64	2	70280	69853
923109	96	1190825143	331911102	55	35	2	70570	70570
923093	95	1187528251	331983541	81	79	2	69656	69532
920105	94	56476147	332021643	104	78	2	68921	68921
10029	103	801505240	719825	85	98	1	71380	71380
10022	104	454295589	916656	86	116	1	71881	71881

Table 3: Catalog format explanations, see also previous Table.

column	unit	description
CPC2		original CPC2 star number
mag	1/10	photographic magnitude, 530–640 nm
RA	mas	right ascension at epoch epRA
SPD	mas	(declination + 90°) at epoch epDC
sx	mas	formal standard error in RAcosDC
sy	mas	formal standard error in DC
nu		number of used images (plates)
epRA	10^{-3}yr	mean epoch of RA (−1900)
epDC	10^{-3}yr	mean epoch of DC (−1900)

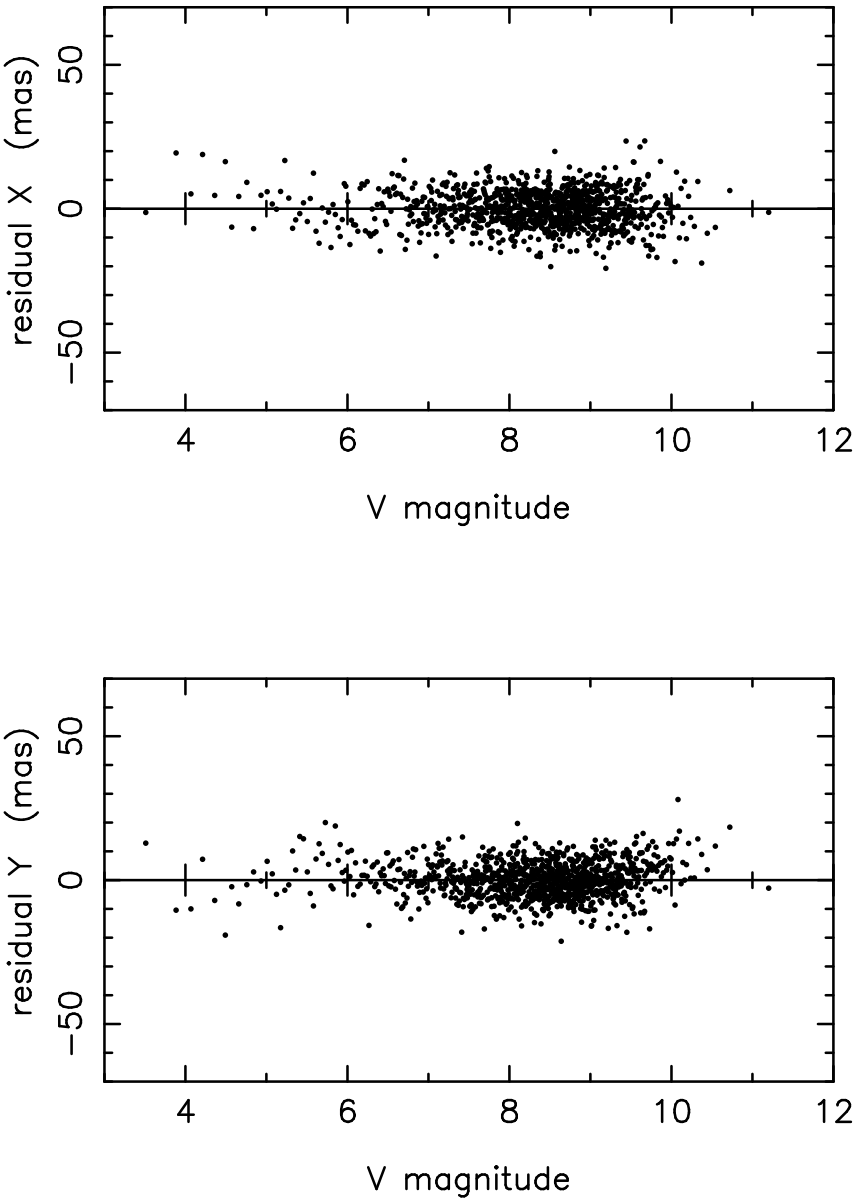

Fig. 1.— Residuals in x and y for the entire catalog data vs. magnitude. One dot is the mean over 200 individual residuals.

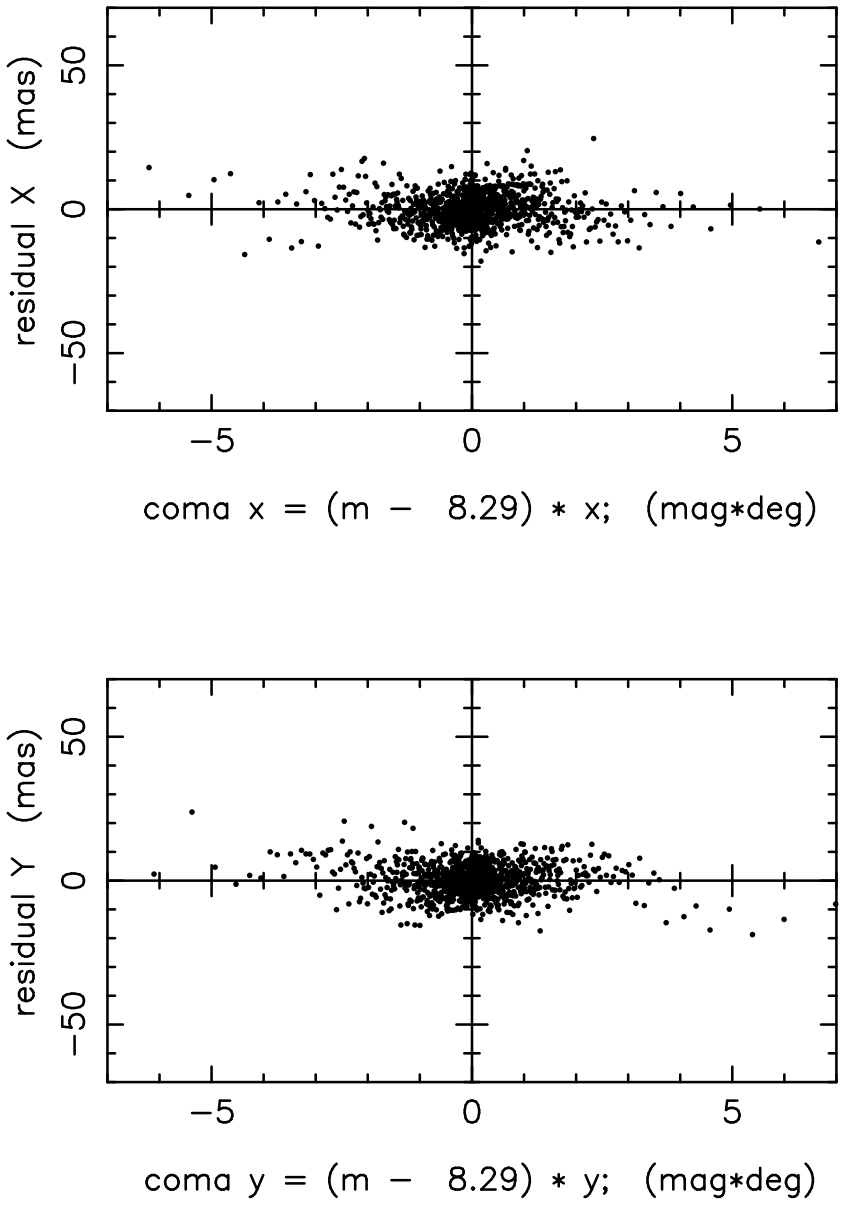

Fig. 2.— Residuals in x and y for the entire catalog data vs. the product of magnitude and coordinate (coma term). One dot is the mean over 200 individual residuals.

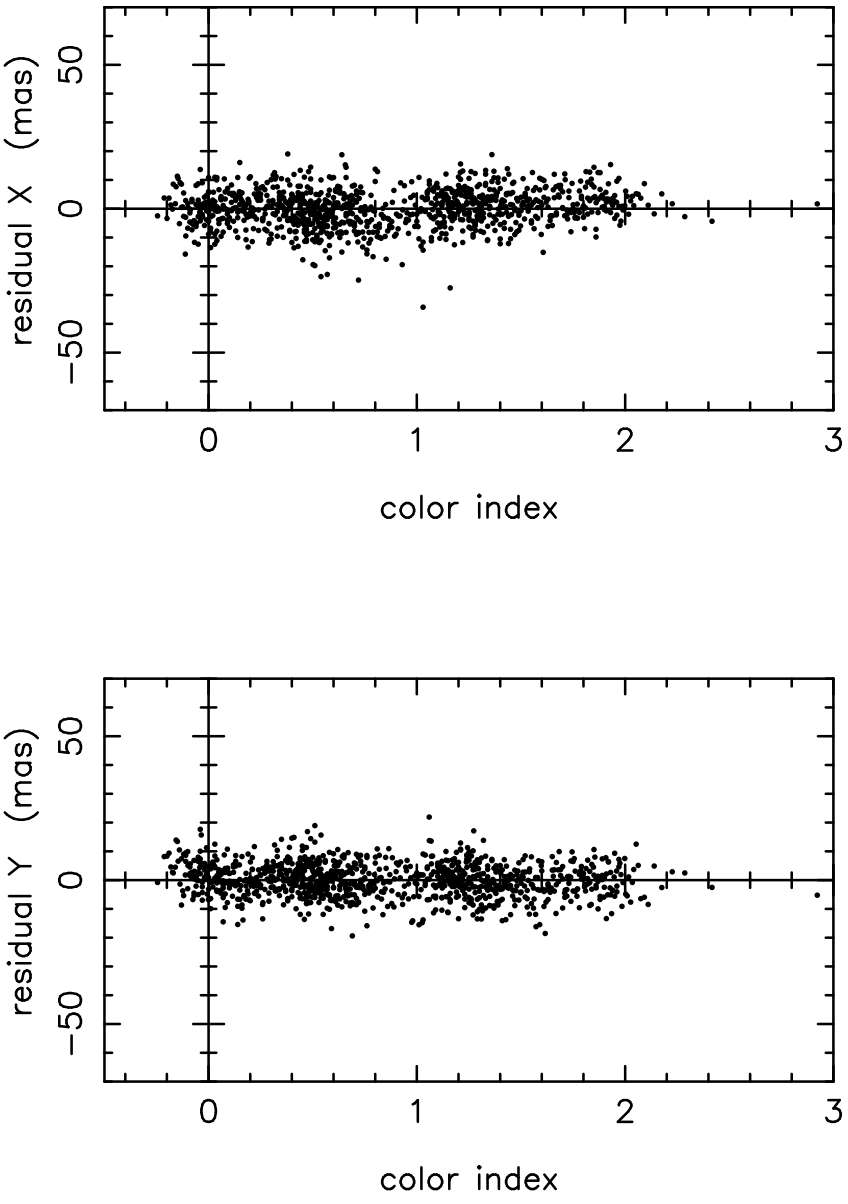

Fig. 3.— Residuals in x and y for the entire catalog data vs. color index. One dot is the mean over 200 individual residuals.

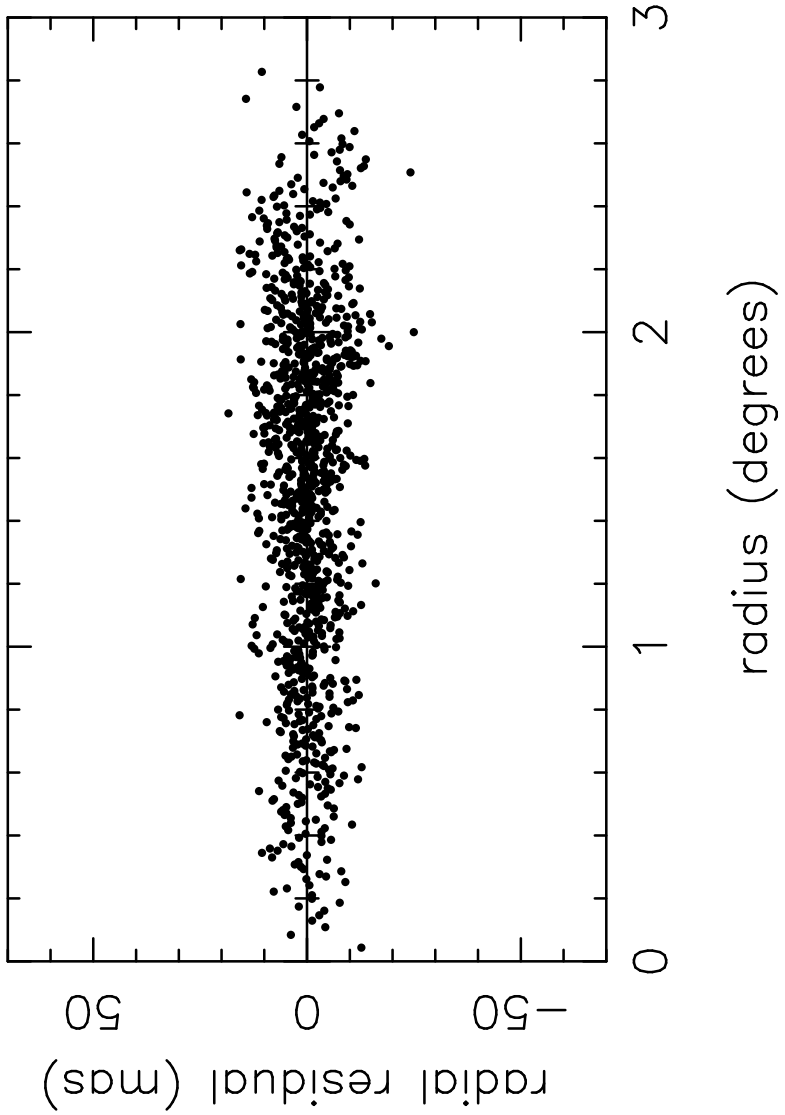

Fig. 4.— Radial residuals vs. radius (distance from plate center). One dot is the mean over 200 individual residuals.

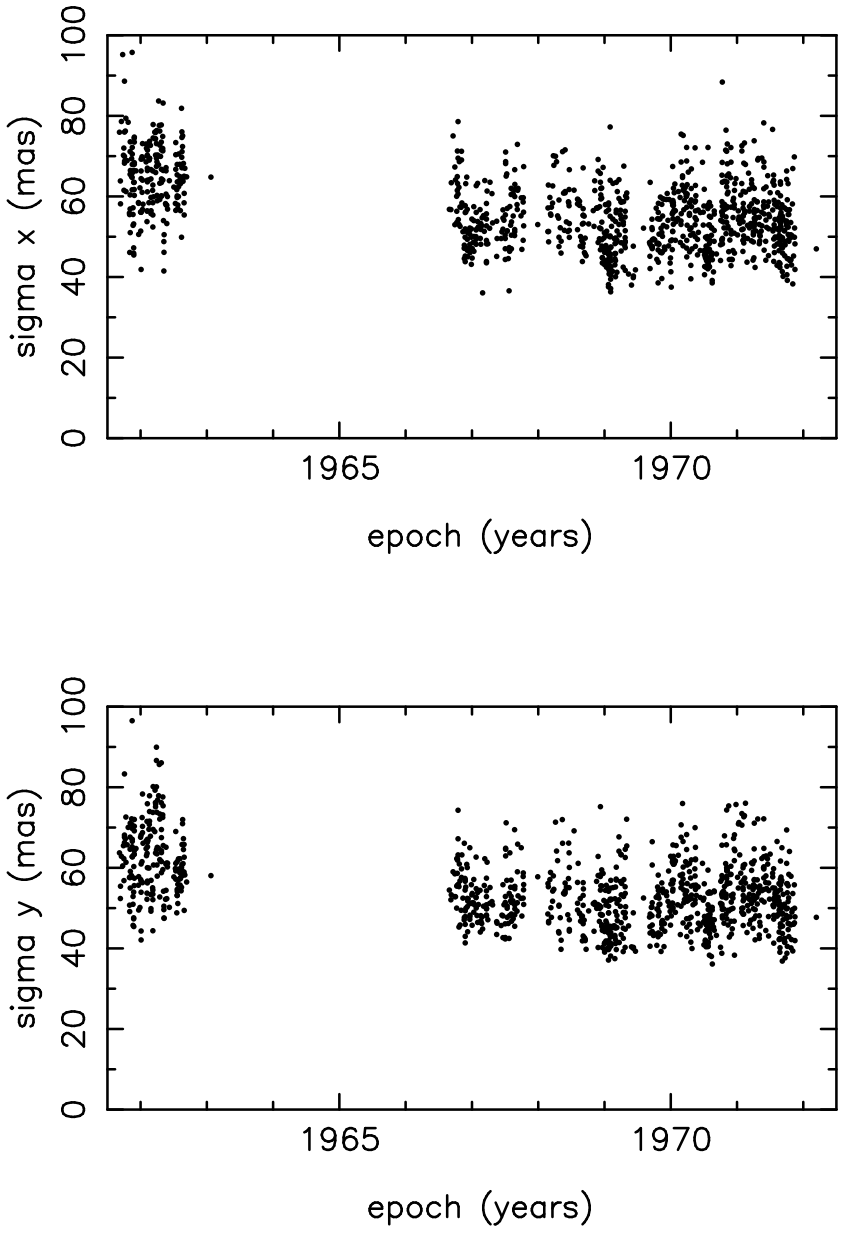

Fig. 5.— Mean quadratic residuals vs. plate epoch. One dot is the mean over 200 individual residuals.

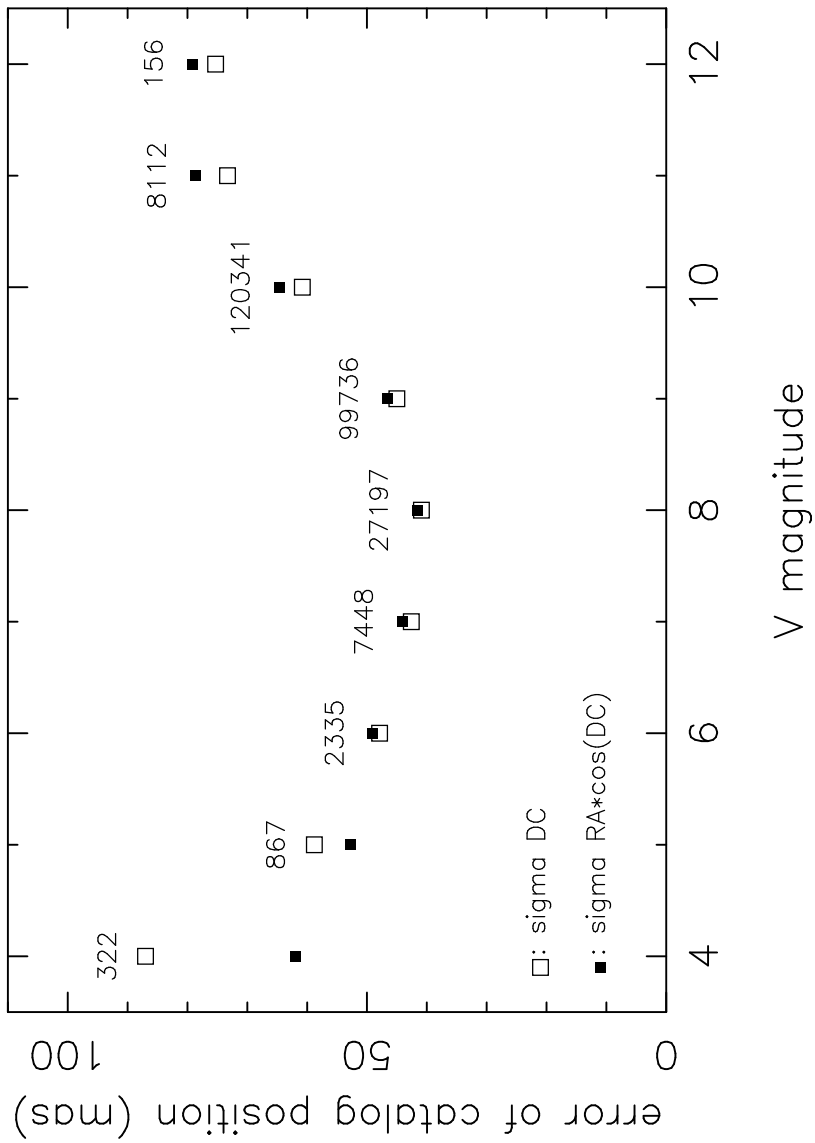

Fig. 6.— Precision (standard error) of positions in the final main catalog as a function of magnitude. The number of stars in each magnitude bin are indicated.

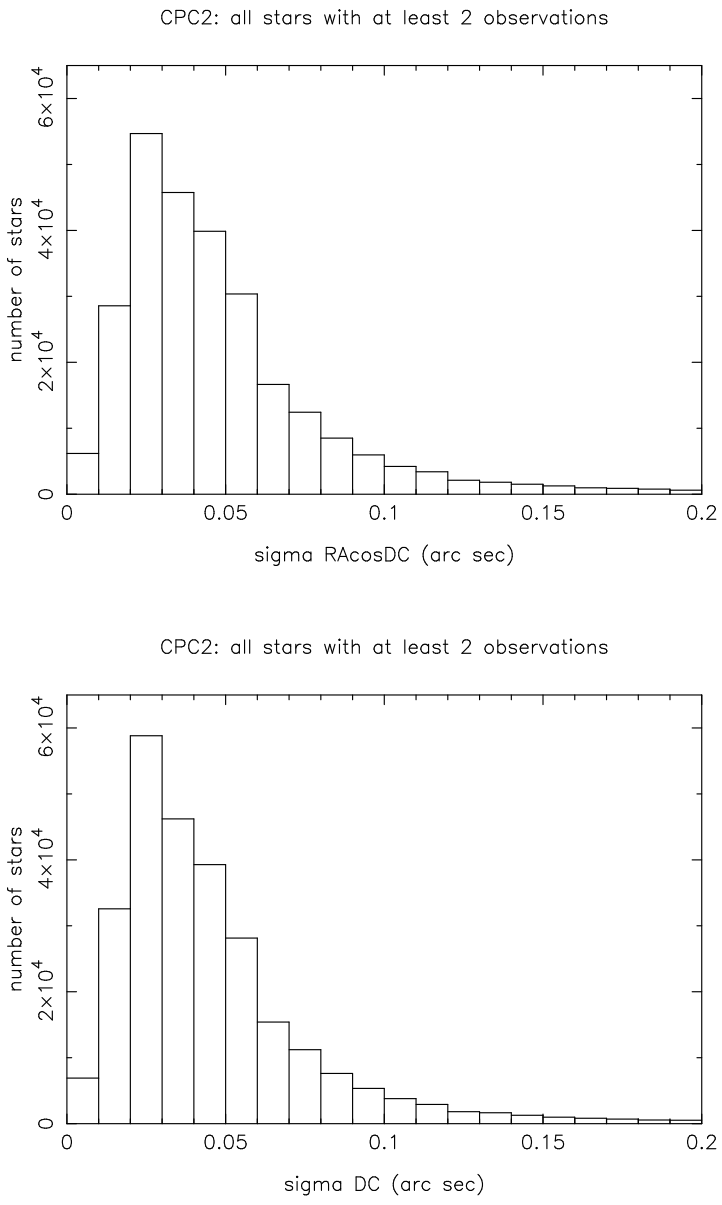

Fig. 7.— Distribution of positional precision of the CPC2 release 2 main catalog.